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PROJECT TRANSIM. A TEN-YEAR PROGRESS REPORT

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This report discusses the significant accomplishments of Project TRANSIM at the University of California, Los Angeles, under ONR Contract N00014-69-A-0200-4009, during the ten-year period ending December 31, 1973. The research and development program is an extension and expansion of earlier work at UCLA and concentrated on further development of general-purpose computer simulation as a versatile and effective analytical tool

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The forces on the foils, both for the injection of water and polymer solutions, were measured using block gauges. It was found that the changes in drag and lift forces are qualitatively different for water and polymer injections as well as for injections on the suction (upper) and pressure (lower) sides of the foils. For example, when the polymer injection is on the suction side of the foils, the lift increases while the drag decreases. On the other hand, when the polymer injection is on the pressure side both the lift and drag decrease, though the lift-to-drag ratio increases.

Based on the present results, and those of other authors, a tentative explanation of the lift increase effect is presented. Since this effect is more pronounced when the injection is performed in the high curvature region close to the leading edge, it is theorized that the polymer injection interacts with the high local velocity gradients along the foil and creates a change in the potential-flow pressure distribution, this change being caused by a local increase of the effective foil curvature due to the visco-elastic behavior of the polymer solution under high strain rates.

International Conference on

Drag Reduction

4th–6th September, 1974

PAPER E2

EFFECT OF DRAG-REDUCING POLYMER INJECTION ON THE LIFT AND DRAG OF A TWO-DIMENSIONAL HYDROFOIL

D. H. Fruman, T. R. Sundaram and S. J. Daugard,

Hydronautics, Incorporated, U. S. A.

Summary

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INTRODUCTION

Following an earlier publication by Wu (Ref. 1), the effects of drag-reducing polymer solutions on the lift of hydrofoils and the thrust of propellers have been investigated by several authors. Examination of the available experimental data shows that under given flow conditions, the drag-reducing fluids may either improve or hinder the hydrodynamic characteristics of lifting bodies depending on their planform and section geometry. For example, Kowalsky (Ref. 2) has reported that the thrust and the efficiency of a three-bladed propeller decreases when operating in a homogeneous polymer solution, while Henderson (Ref. 3) has shown that the thrust decreases and the efficiency increases in the case of a two-bladed propeller. This discrepancy may be ascribed to the differences in the number and geometry of the blades of the two propellers as well as in the particular range of values of the advance coefficient used in the tests.

Similar contradictory results have also been published concerning hydrofoils. Sarpkaya and Rainey (Ref. 4) have stated that homogeneous dilute polymer solutions have no discernible effect upon the mean forces produced by a two-dimensional symmetrical hydrofoil. On the other hand, Wolf and Cahn (Ref. 5) have reported that, for a tapered three-dimensional hydrofoil in homogeneous polymer solutions, a significant shifting of the lift curve equivalent to a reduction of about three to four degrees in the foil angle occurs. This effect was noticed at high free-stream velocities even for the lowest concentration of the polymer. Again, the differences in the geometry of the foils and in the test conditions may be responsible for the difference in the two results.

The effects of injecting a drag-reducing polymer into the boundary layers of three-dimensional and two-dimensional hydrofoils have been investigated respectively by Wolf and Cahn (Ref. 5) and Lehman and Suessmann (Ref. 6). The former authors found that polymer injection on the suction side of a tapered three-dimensional hydrofoil produced a significant lift reduction, while the latter authors report that the lift can either increase or decrease depending on whether the injection is on the suction (upper) or pressure (lower) side of the hydrofoil.

The results of Lehman and Suessmann represent the first systematic attempt to gain some understanding of the "lift effect" problem. However, since their tests were limited to a single foil section, NACA 6500, 76.2 cm in chord, and free stream velocities up to only 5 m/sec, further research is required to extend their results to other foil sections and to a wider range of flow conditions.

The present paper describes the effects of injecting a drag-reducing polymer solution into the boundary layer of two NACA 63 two-dimensional symmetrical hydrofoils, 10 and 20 cm in chord, with 20 and 10 percent relative thickness, respectively. The maximum polymer injection velocity was about 20 percent of the free-stream velocity which ranged from 5 to 13 m/sec.

The results indicate that the injection of the drag-reducing polymer produces an increase of the lift-drag ratio of the foils, regardless of

whether the injection is made on the suction or pressure side of the foil surface. The magnitude of the effect depends on the relative thickness and chord of the foil, on the incidence angle and on the injection and free stream velocities.

EXPERIMENTAL PROCEDURE

The tests were performed in the HYDRONAUTICS High Speed Channel (Ref. 7), Figure 1, modified to obtain a two-dimensional flow, thus eliminating the free surface effects which may have otherwise occurred at the high speeds used in the tests. This modification incorporates a roof with a specially designed transition which was attached to the original free surface sluice gate of the channel. An oversized hole allows free passage of the models through the roof. The foils were supported vertically by means of a block gauge arrangement and an incidence-control system, as indicated in Figure 2. In order to minimize air entrainment, which may be induced by the low pressures on the suction side of the foil, the upper side of the roof was flooded. To create the best conditions for a two-dimensional flow and to avoid secondary flows between the lower and upper section of the roof, an end plate was fitted to the cross section of the foil, being free to move with it (Figure 2). Since the tests were designed to obtain comparative measurements of the hydrodynamic characteristics of the foils with and without injection, no specific investigation of the end gap effect was made during this study. Results published elsewhere (Ref. 8) demonstrate, that with these particular precautions, the lift and drag coefficients of the hydrofoils are close to other known two-dimensional values.

The cross section of both foils was a NACA 63 symmetrical profile. The small foil, Figure 3, was 10.16 cm in chord with 20 percent relative thickness and the large foil was 20.32 cm* in chord with 10 percent relative thickness. Therefore, the absolute thickness of both foils was the same, 2.032 cm. In both models, the injection slits were situated at a 10 percent chord distance from the leading edge, so that the actual distances for the two are 1.016 and 2.032 cm.

The injection slits were designed so as to decrease the possible local perturbations which may be produced by the ejected fluid. As shown in Figure 4, the inclination of the slits, relative to the foil tangent at the injection station, was 7^{o} for both foils. Based on the empirical relationship describing the diffusion of a dilute polymer solution over a flat plate obtained by Fruman and Tulin (Ref. 9), the gap of the injectors was selected to be 0.0127 cm for the small foil and 0.0254 cm for the large foil.

The foils were fabricated from aluminum and then chrome plated. A silicone spray was applied to the surface of the foils in order to preserve the quality of the finish.

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*Henceforth these foils will be referred to as the 10- and 20-cm chord foils.

The free stream velocity in the test section was measured with a 3 mm diameter Prandlt tube placed ahead of the hydrofoils. Though it is known that, in general, the stagnation pressure readings of such tubes are affected by the polymer solutions, it is believed that in the present case the relatively small build-up of polymer concentrations in the re-circulating water and the relatively large diameter of the probe make any significant errors highly improbable.

The lift and drag forces were measured by means of four reluctance-type block gauges attached to the foils as shown in Figure 2. The total lift and drag load capacities of these gauges were 90 and 16 kg, respectively. The electrical output signal from the gauges was integrated over a ten-second period and the average values were recorded.

The injected fluids were contained in a nine-gallon reservoir, which was pressurized so as to drive the fluids into the injection slit through a pipe system. The pipe system contains a regulating valve and a rotameter for the determination of the flow rate. The rotameter was calibrated with water only, but was also used for the polymer solutions. Independent checks showed that the rheological characteristics of the dilute polymer solution does not significantly affect the calibration of the rotameter.

The polymer used in these tests was poly(ethylene oxide), POLYOX WSR 301*, which has been demonstrated to be a highly efficient drag-reducing agent. The method of preparation of the dilute polymer solutions has been described elsewhere (Ref. 9). A constant polymer concentration of 200 ppm was used in all the tests.

ACCURACY AND REPEATABILITY OF THE TESTS

As previously outlined, the objective of the test program was to investigate the relative changes caused in the hydrodynamic forces on the foil by injections of water and dilute polymer solutions. Of course, for a proper assessment of these small changes it is essential to ascertain the basic accuracy and degree of repeatability of the measurements under conditions of zero injection.

Due to certain inherent features of the experimental equipment and procedures used in the tests, some inaccuracies may arise. The inaccuracies may be due to inadequacies in the measuring equipment (such as the force gauges, the velocity probe and the manometer), unsteadiness of flow conditions ahead of the hydrofoils (turbulence as well as low-frequency fluctuations) and model deflection under loads.

The force gauges are sufficiently linear in the operating range of the tests for any errors due to nonlinearities to be negligibly small. Moreover, since the force measurements are obtained from a ten-second integration of the instantaneous gauge output, errors due to high-frequency velocity fluctuations are unlikely. However, the effective

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*Manufactured by Union Carbide Corporation.

mean velocity during the integration period can be different from the "nominal" channel speed indicated by the mercury manometer associated with the velocity probe. For the purpose of the present investigation, however, the "nominal" free stream velocity was used instead of the average value. Random errors, such as those created by the deflection of the foil under loads, are difficult to evaluate and may adversely affect the accuracy as well as repeatability of the tests. The deflection of the foil under loads, especially at high foil angles, is inherent to the mechanical arrangement of the foil mounting. A more sophisticated arrangement which would avoid these deflections was beyond the scope of the present program.

A systematic analysis of the variances in the lift and drag coefficients of both hydrofoils without injection indicates a mean deviation of about ±2 percent for practically all the free-stream velocities. These results are summarized in Figures 5 and 6 for the 10 and 20 cm chord hydrofoils, respectively. It should be pointed out, however, that at the lower free stream velocity (5 m/sec), the drag measurements indicate a relatively larger deviation from the mean values. This result is not surprising since at the relatively small Reynolds number appropriate to the low-speed case, boundary-layer transition on the foil is quite sensitive to the turbulent conditions in the test section, the foil surface roughness, etc.

The hydrodynamic characteristics of the foils were insensitive to the build-up of an homogeneous polymer concentration in the recirculated water, since the polymer solution degrades when circulated through the 1000 HP centrifugal pump of the high speed channel. Moreover, the concentration build-up was never allowed to exceed 1 ppm

PRESENTATION OF THE RESULTS

The effects of water and polymer injection on the drag of the foils at zero angle of attack are shown in Figure 7. For water injection, the percentage change in drag is positive and decreases as the velocity increases. On the other hand, polymer injection decreases the drag over the entire range of speeds tested, though the effect becomes more pronounced as the free-stream velocity increases. The results also indicate that an increase in the injection velocity of the polymer solution produces an increase in the drag reduction. Finally, for the same free-stream and injection velocities, the drag reduction is larger for the larger foil. It can be seen from Figure 7 that the differences in drag reduction between the 10 and 20 cm foils are well correlated in terms of their differences in Reynolds number alone.

Even at zero angle the lift of the foils is affected by the injections, Figure 8. While the water injection is accompanied by the production of a negative or negligible lift, depending on the length and relative thickness of the foil, the polymer injection generates a positive lift on both foils over practically the entire ranges of free-stream velocities.

The opposite effects of the water and polymer injection at zero foil angle are clearly demonstrated by the tests performed at a small foil angle, Figure 9. There also exists very significant differences in lift effects, depending on whether the polymer injection is made on the suction (upper) or pressure (lower) side of the foils. In the first case, the lift increases with increasing free-stream velocity, while in the second case, the lift decreases with increasing free-stream velocity.

Figures 10 and 11 present the changes in lift and drag associated with two different rates of injection of the POLYOX WSR 301 solution, for the 10 cm chord hydrofoil and foil angles of 2.5 and 5°, respectively. It can be seen from the figures that the results for the two cases are qualitatively the same, though the smaller angle of attack seems to have produced the larger quantitative changes.

The results of the polymer injection for the 20 cm chord hydrofoil and a 2.5° foil angle, are presented in Figure 12. In this case also, the lift increases when the injection is made on the suction side, while it decreases when the injection is made on the pressure side. In both cases the drag is significantly reduced. Although the lift and drag effects under polymer injection conditions are of interest in themselves, the ultimate effectiveness of the injection in improving the hydrodynamic characteristics of the foil can only be assessed by considering the changes in the lift-drag ratio. Figure 13 shows the difference between the lift-drag ratio produced by polymer injections on the suction and pressure sides of the 10 cm chord foil. In both cases the lift-drag ratio is significantly increased, although the variations with the free-stream velocity are significantly different. The results, for the 20 cm chord foil are similar to those for the 10 cm chord hydrofoil.

DISCUSSION OF THE RESULTS

Several important conclusions can be drawn from the results described in the previous section. These are:

(i) With polymer injection the drag is generally reduced regardless of whether the injection is on the suction or pressure side of the foil surface. For the same foil angle, rate of injection and polymer concentration, the drag reduction effect appears to be well correlated with the Reynolds number.

(ii) When the polymer solution is injected on the upper surface (suction side) of the hydrofoils, there is, in general, an increase in lift. However, at the lowest free-stream velocities tested, there appears to be a slight decrease in lift. The magnitude of the lift effect, for equal rates of injection, polymer concentration and Reynolds number, appears to be strongly dependent on the slenderness ratio of the foil.

(iii) When the polymer solution is ejected into the pressure side of the foil surface, increases or decreases in lift occur depending on the foil angle, relative thickness of the foil, and the Reynolds number.

(iv) Water injection under conditions corresponding to those tested either produces negligible effects or effects opposite to those with polymer injection.

The above conclusions are in general qualitative agreement with those of Lehman and Suessmann (Ref. 6). Specifically, the present results firmly establish the lift-increase and drag-reduction effects associated with polymer injections on the suction side of an hydrofoil. The present results also demonstrate that the increase in lift is strongly dependent on the relative thickness of the foil. Figures 8, 10a and 12a show that, for the same Reynolds number, 1.3×10^6, a decrease of the relative thickness from 20 to 10 percent produces about a tenfold decrease in the lift effect.

It is unlikely that, for the symmetrical foil shapes and the relatively small incidences considered here, separation of the boundary layer from either the upper or lower surface of the foil occurs (Refs. 10, 8) in water at the above Reynolds numbers. Therefore, if polymer injection affects the structure of the boundary layer and its separation at all, then the only effect which may be expected is a lift reduction due to an advanced separation. Since the test results demonstrate the opposite, it appears that the observed increases in lift can only be explained in terms of a changed potential-flow pressure distribution on the hydrofoil surface. The data indicate that the observed increases in lift may be directly related to the magnitude of the velocity gradient (and hence the pressure gradient) along the surface of the foil in the region close to the injection slit. In general, the velocity gradient increases on the upper surface of an hydrofoil and decreases on the lower surface when the angle of incidence increases. The absolute values of the lift increases due to polymer injection are poltted in Figure 14 against the angle of incidence. It can be seen that the lift changes increase continuously with the angle of incidence, as would be expected if the former were dependent primarily on the magnitude of the velocity gradient at the location of the injection slit.

A definitive explanation for the observed lift increase will have to await detailed measurements of the pressure distributions on the hydrofoil. Systematic measurements should also be made for various locations of the slit relative to the leading edge of the foils. In this context it is relevant to note that the results of Lehman and Suessmann, clearly indicate that the lift increases are larger when the injection on the upper surface is performed closer to the leading edge of the foil.

CONCLUDING REMARKS AND RECOMMENDATIONS

The present tests demonstrate that substantial increases in the lift-to-drag ratio of hydrofoils and performance of propellers can be obtained by polymer injection from suitably located injection slits. Thus at relatively low velocities and incidence, injection into the lower (pressure) side of the foils seems to be more effective, while at higher velocities injection into the upper (suction) surface seems to be definitely superior. Moreover, injection in regions of high velocity gradient (that is, closer to the leading edge) seems to lead to better results.

The present tests have only dealt with two-dimensional hydrofoils. However, from consideration of practical application, three-dimensional effects are likely to be quite important, since a significant induced drag may be expected to arise. Nevertheless, the present tests offer considerable evidence on the substantial lift augmentation that can be achieved with proper polymer injection.

ACKNOWLEDGMENTS

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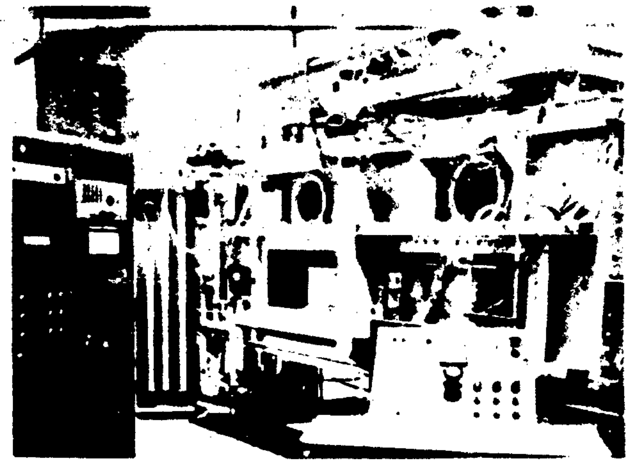


Fig. 1 Hydronautics, Incorporated high-speed channel

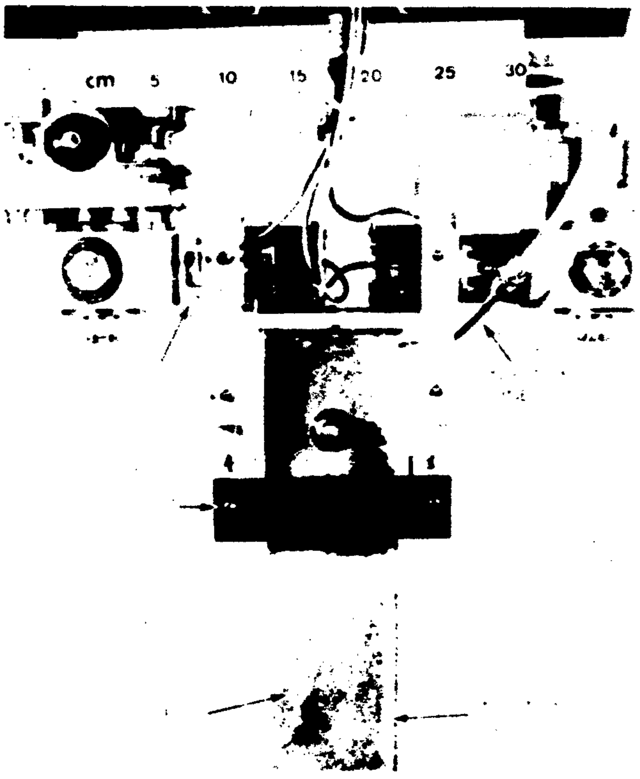


Fig. 2 Block gauges arrangement with mounted hydrofoil

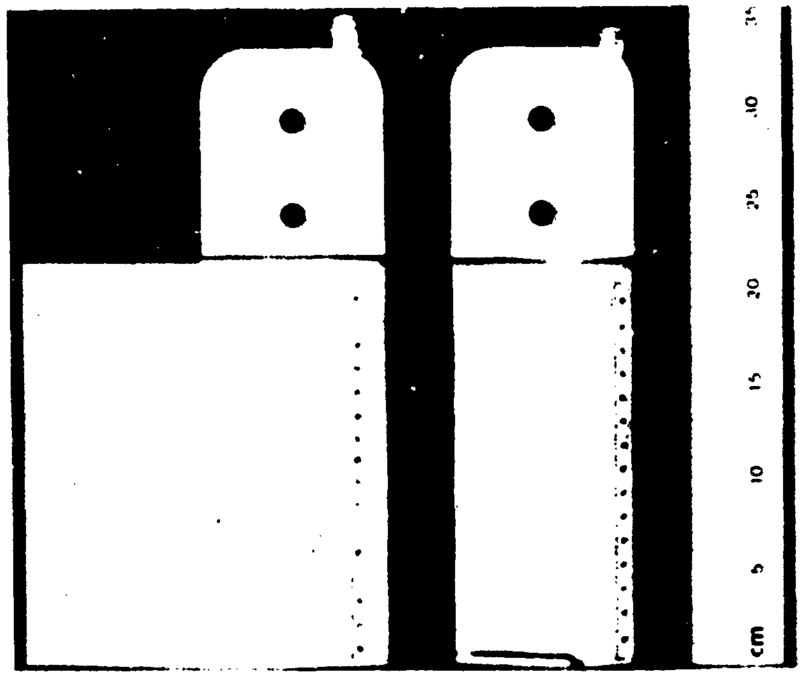
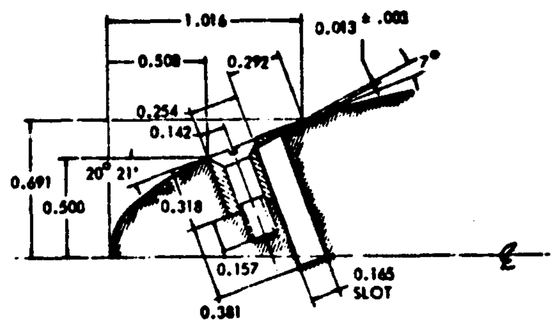
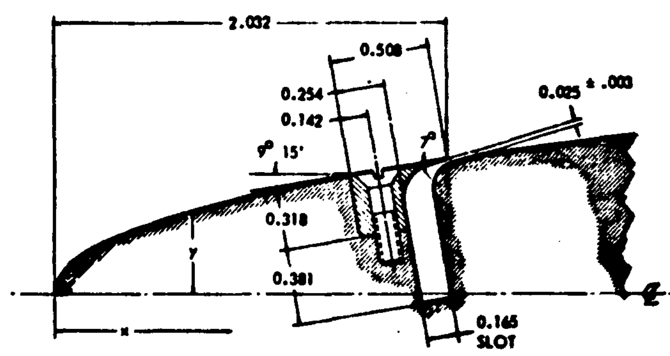


Fig. 3 NACA 63 two-dimensional hydrofoils



(a) FOIL LENGTH: 10 cm



(b) FOIL LENGTH: 20 cm

Fig. 4 Design of the injection slit (all indicated dimensions are in centimeters)

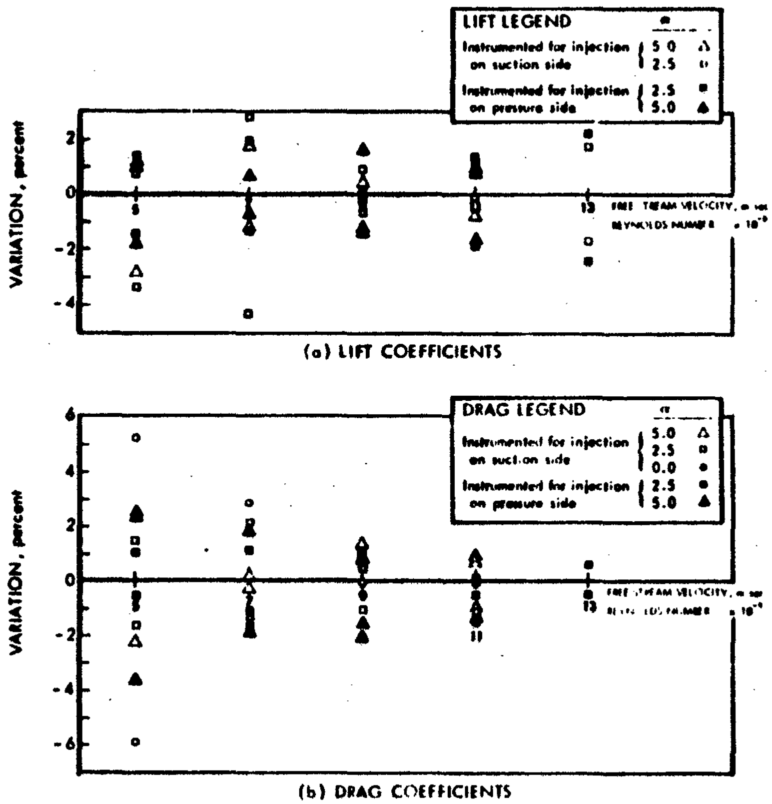


Fig.5 Precision during repetition of measurements with the 10 cm foil

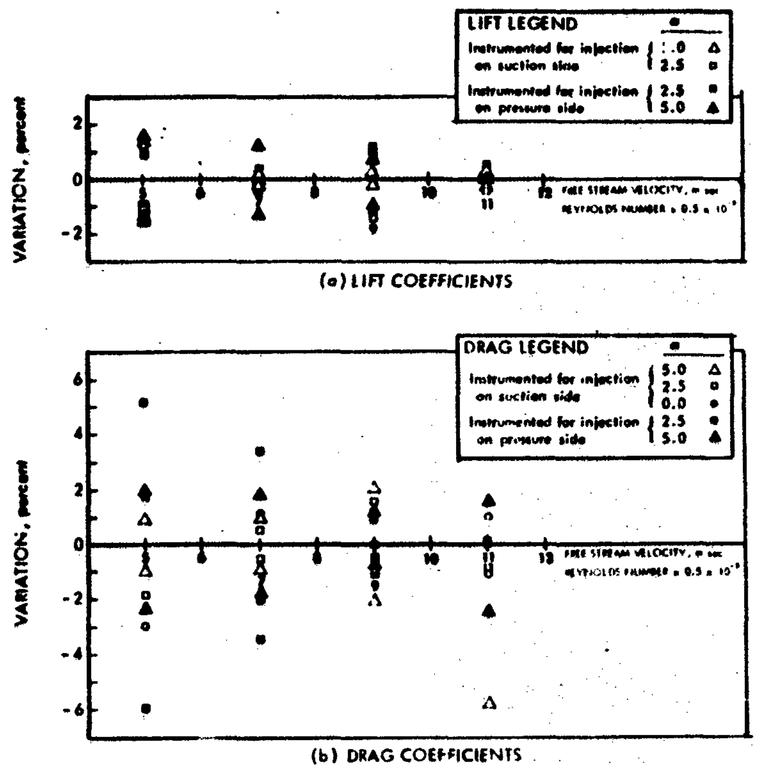


Fig.6 Precision during repetition of measurements with the 20 cm foil

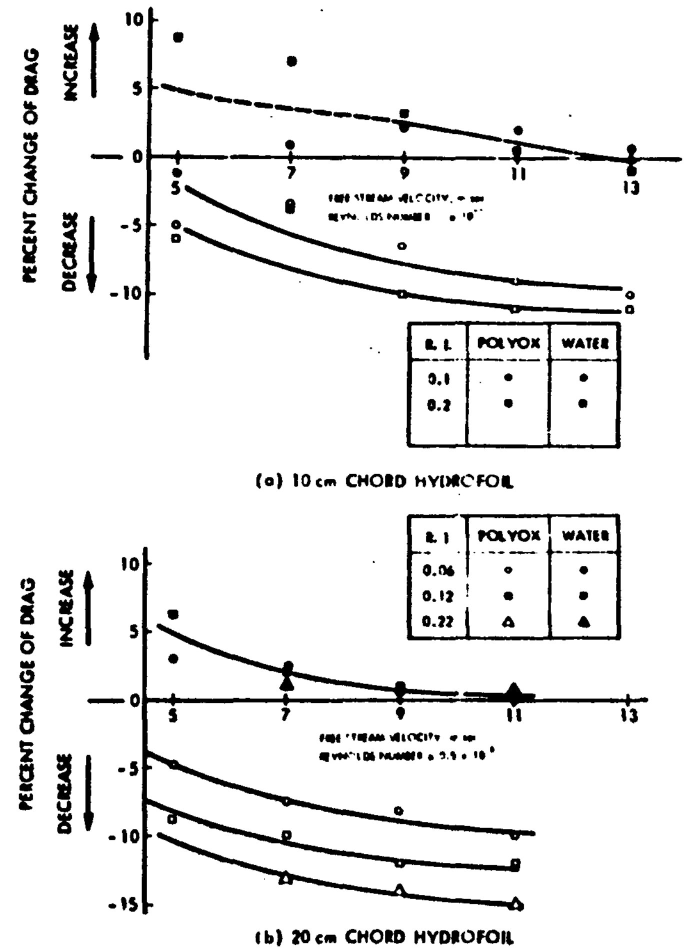


Fig. 7 Effect of water and polymer injections on the drag of the hydrofoils at 0° foil angle

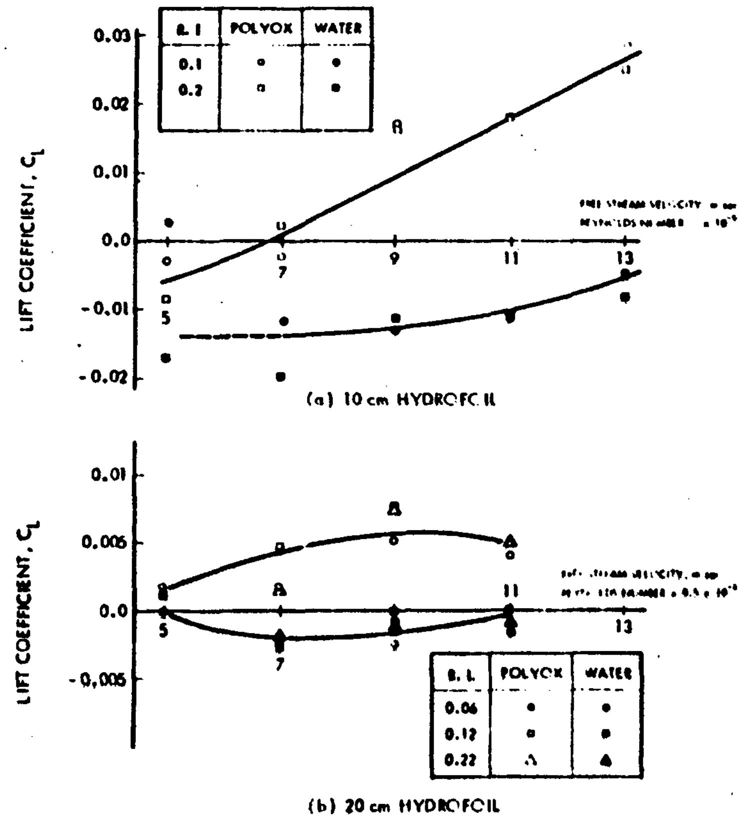


Fig. 8 Effect of water and polymer injection on the lift of the hydro foils at 0° foil angle

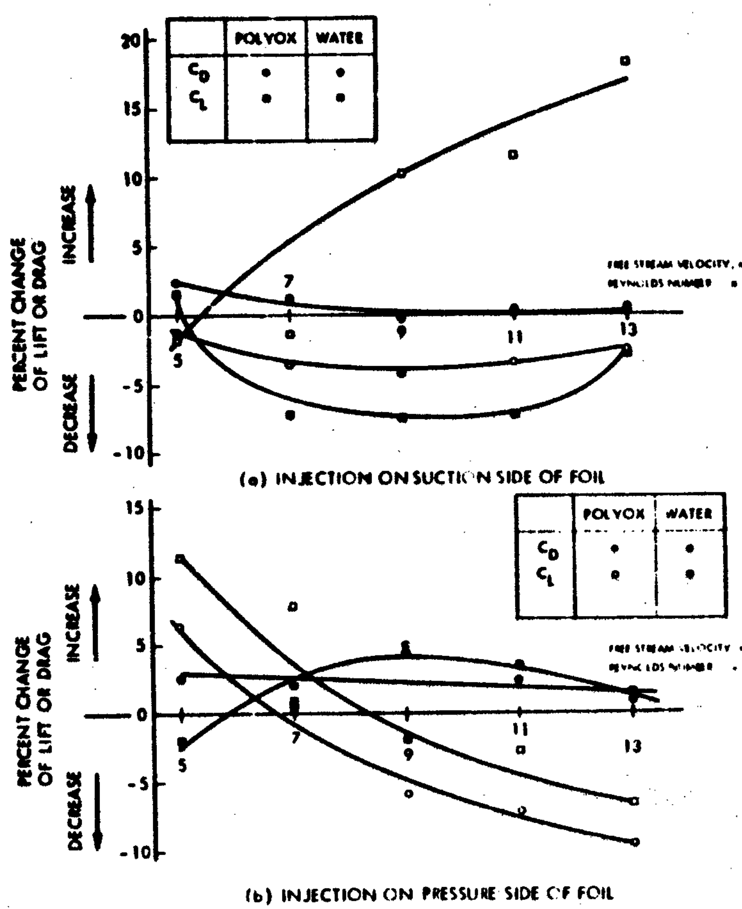


Fig.9 Comparison between water and polymer injection effects on the lift and drag of the 10 cm chord hydrofoil at 2.5° foil angle and injection rate 0.1

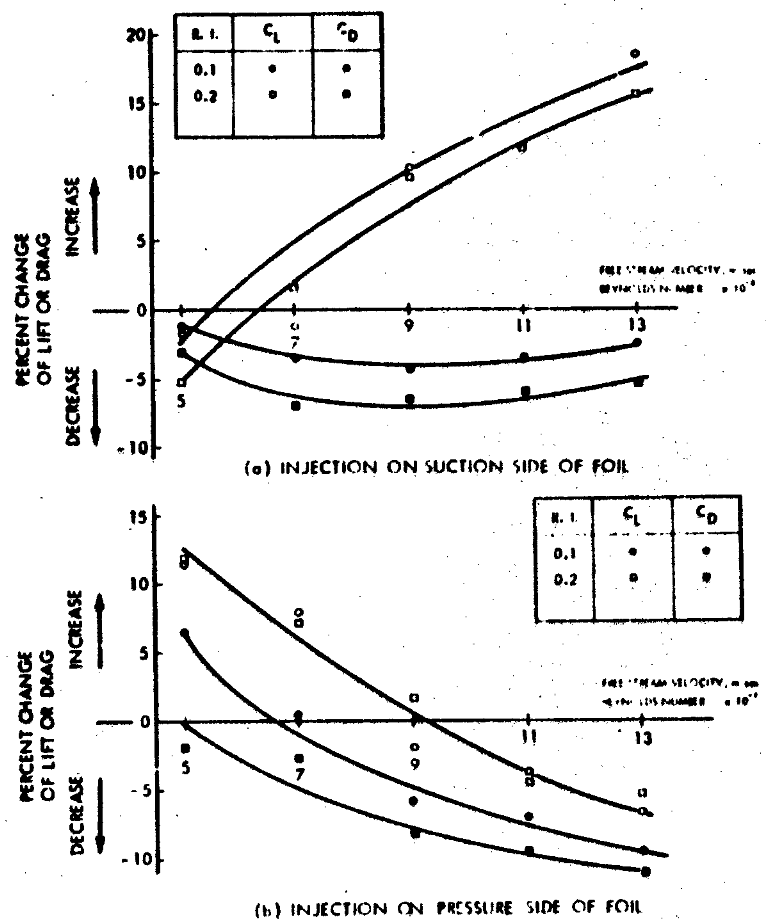


Fig.10 Effect of an injection of 200 ppm of polyox WSR 301 on the lift and drag of the 10 cm chord hydrofoil at 2.5° foil angle

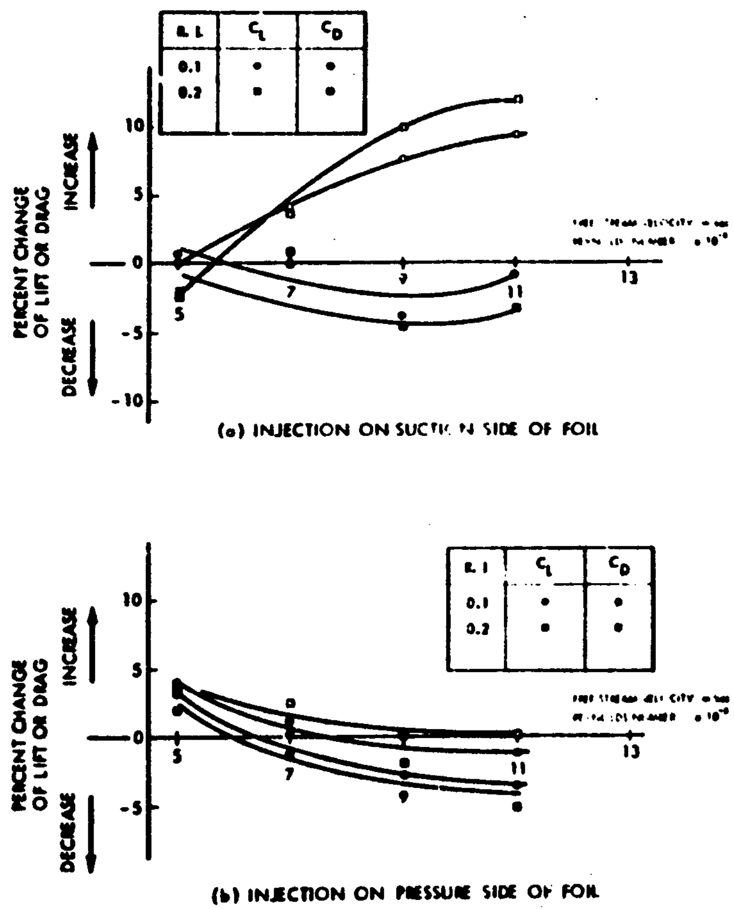


Fig. 11 Effect of an injection of 200 ppm of poiyox WSR 301 on the ligt and drag of the 10 cm chord hydrofoil at 5° foil angle

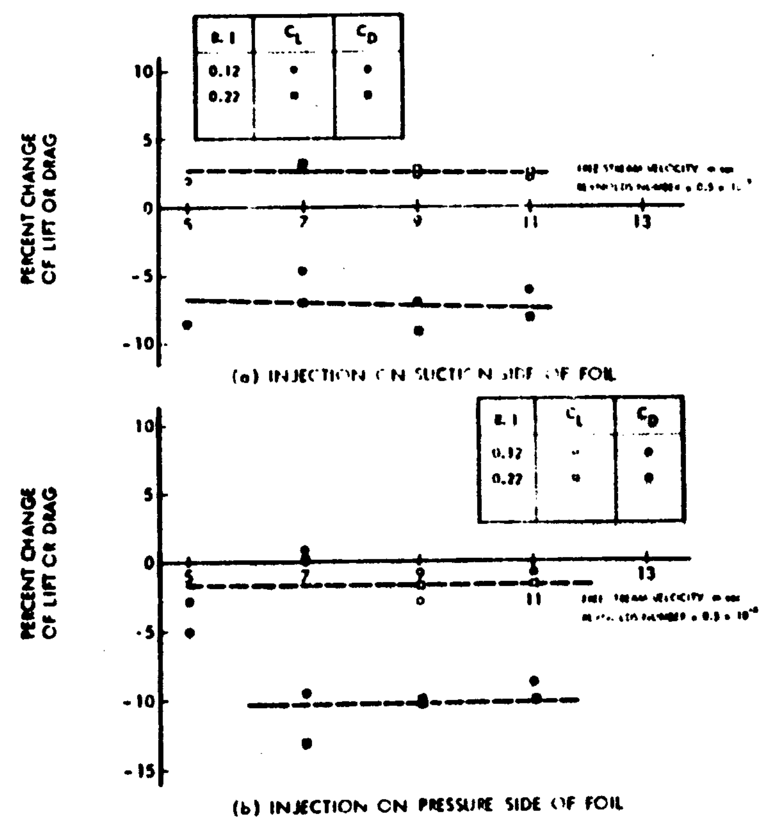


Fig. 12 Effect of an injection of 200 ppm of polyox WSR 301 on the lift and drag of the 20 cm chord hydrofoil at 2.5° foil angle

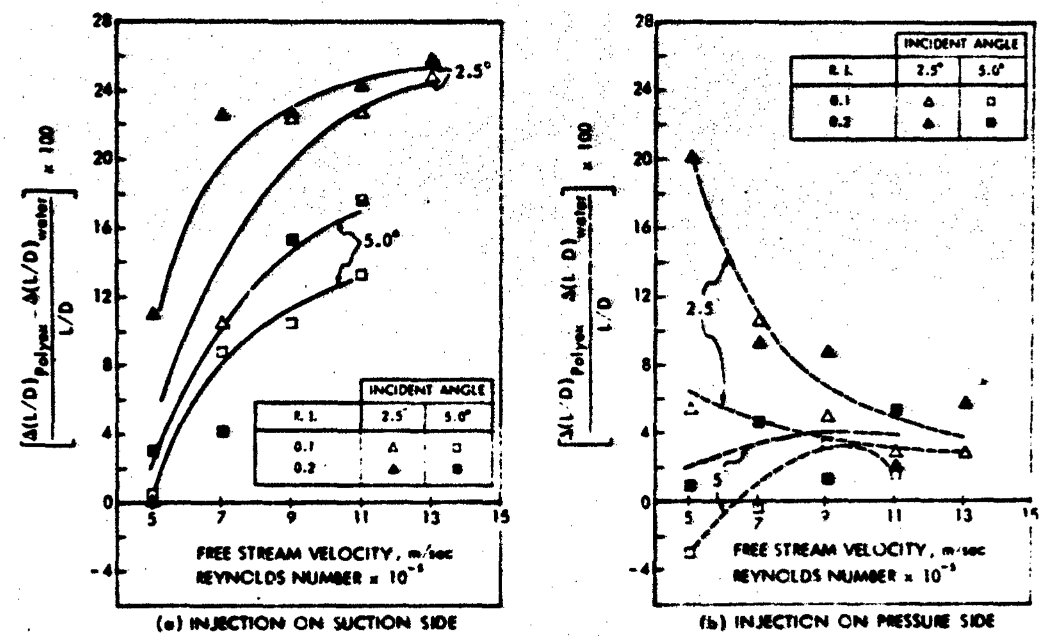


Fig. 13 Comparison of the percent change of lift-drag ratio with the polyox injection (Relative to that for water) using the 10 cm foil

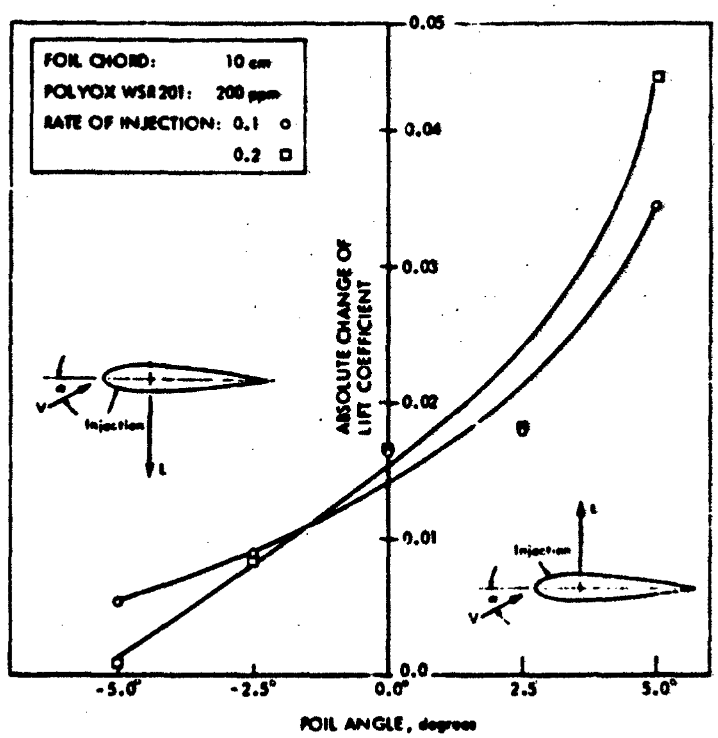


Fig. 14 Absolute change of lift coefficient as function of the foil angle